Luminosity staged, low risk ERL-ring eRHIC approach

- Risk mitigation approach
- Staged hadron cooling
- High electron current risks
- Reducing number of SRF cavity types
- Longer linac consideration (2 GeV linac)
- Summary

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Technological risks in present baseline design

- Beyond state-of-the-art:
  - *High energy fast hadron cooling*
  - *Large polarized electron current: 50 mA*
  - *High power multipass ERL: 20 GeV, 16 passes, up to 700 mA total current in the linac*

- Novel applications of proven technologies:
  - *Crab-crossing with hadron beam*
  - *Fixed Field Alternating Gradient Lattice for recirculating passes*

- Cost and effort risks:
  - *Large number of different SRF cavity types: 10*

Risk mitigation

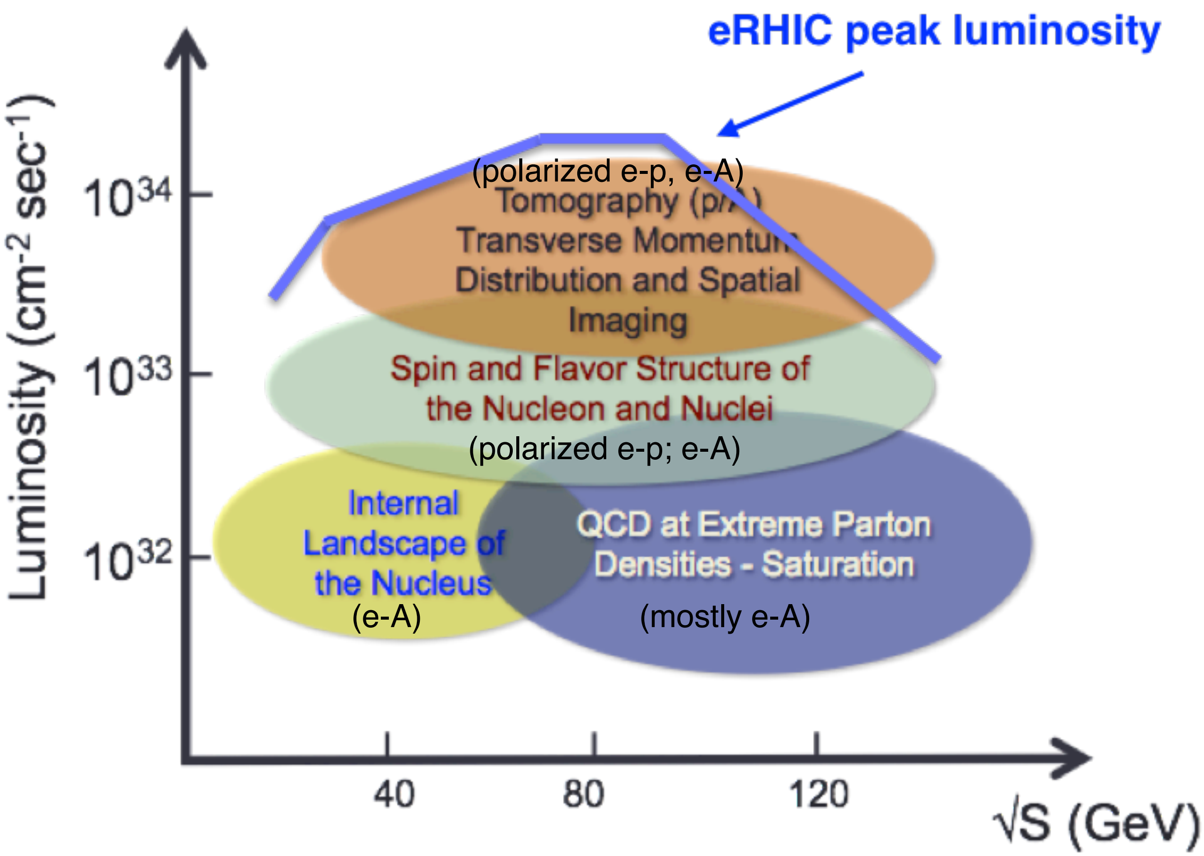
- While baseline design allows to reach luminosities above 10^{34} cm^{-2} s^{-1} the design technological risks can not be ignored.

- There is a solid R&D program, but its timescale is short (3 years), and some of R&D items may require longer time to prove corresponding technology.

- Presently pursued design risks mitigation program includes:
  - revising and re-optimizing the baseline design to reduce risks
    - *preserving luminosity and the energy range*
    - *the balance of risks reduction vs cost increase*
  - demonstrating possible backup solutions for highest risks
    - *even if resulting in lower luminosity*
  - consideration of staging scenarios based on the backup solutions

Thus developing:
Luminosity staged, low risk ERL-ring eRHIC

eRHIC Physics Program: possibility of natural luminosity staging



Luminosity and limiting factors

- Luminosity through limiting factors:

$$L = \frac{\gamma^2}{4\pi e} \frac{I_e N_p \sigma'^{*2}_p}{\varepsilon^2_{np}}$$

  - Electron current (I_e) limits: synchrotron radiation power (2.5 MW) and polarized source capability (50 mA)
  - Proton angular spread is limited by experimental requirements (~100 μrad at 250 GeV)
  - Other assumed limiting factors: $\xi_p = 0.015$, $\Delta Q_{sp} = 0.08$

- Small proton transverse emittance (efficient transverse cooling) is major factor for highest possible luminosity

- Note: smaller transverse emittance allows for smaller β^* and, hence, for shorter proton bunch length (longitudinal cooling)

Hadron Cooling

- Baseline design: Coherent electron Cooling

- The backup under consideration: electron cooling
- Elector cooling was a part of eRHIC baseline design in eRHIC ZDR (before the CeC idea):
  - Pre-cooling of protons at the injection
  - Slow cooling of protons up to 50 GeV
  - Cooling of gold ions up to 100 GeV/u

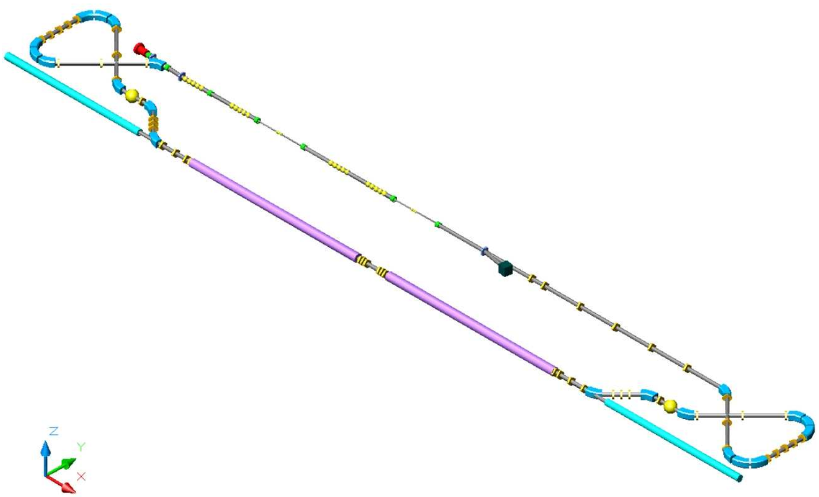


Figure 3.1: Schematic layout of the RHIC electron cooler (system shown for one ring). The photoinjector is shown in red, the superconducting energy-recovery linac is shown in yellow, the solenoid in purple and a section of the RHIC ring is shown in green.

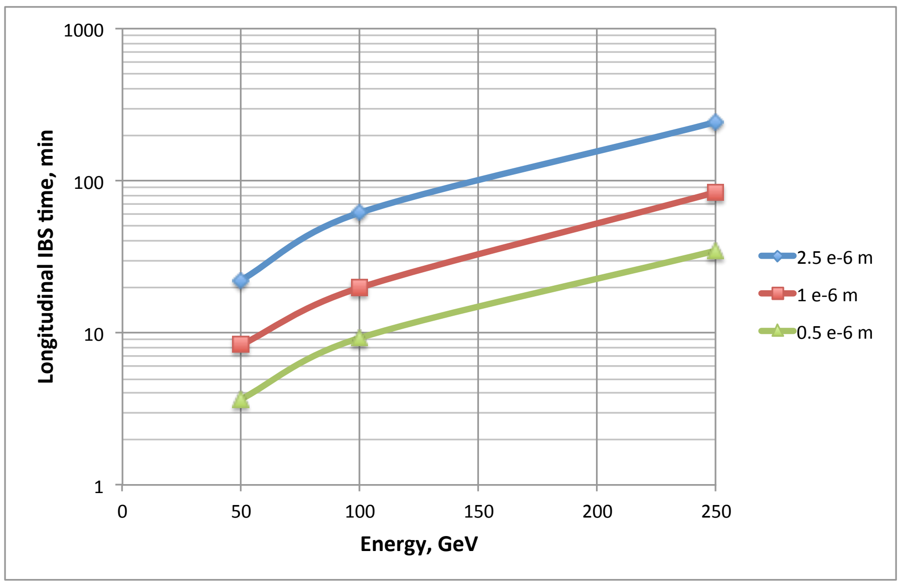
Magnetized beam cooler (developed for RHIC and eRHIC):

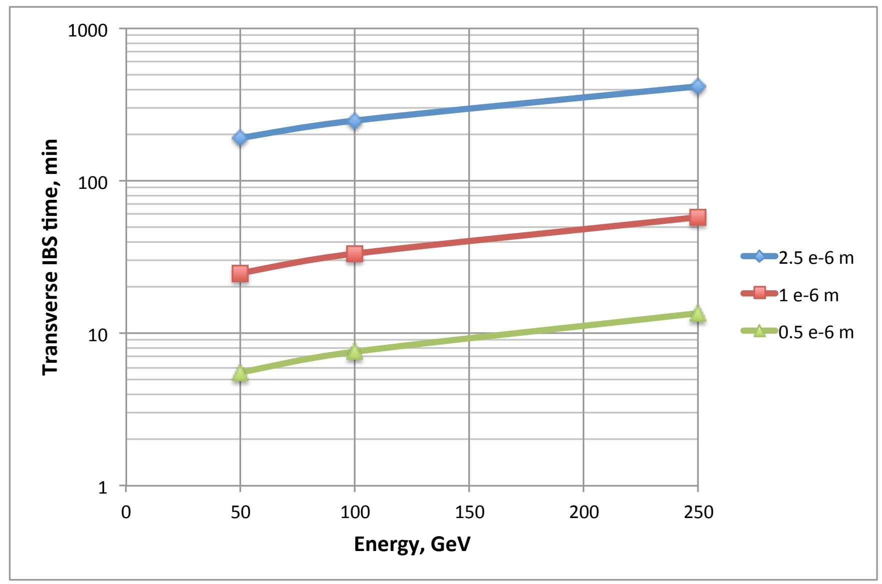
- ERL
- 100 mA electron current
- 1 T solenoids (26 m)

Proton IBS growth time

Assumed beam parameters:
bunch intensity = 3 E11
rms momentum spread = 5e-4
rms bunch length = 20 cm

"Betacool" calculation, A.Fedotov





The longitudinal (left plot) and transverse (right plot) IBS growth times are shown for three different values of normalized transverse emittance.

IBS time evaluation and possible e-cooling options

Assumed:

- bunch intensity = 3 E11
- rms momentum spread=5e-4
- rms bunch length = 20 cm
- proton energy = 250 GeV

Normalized rms emittance, E-6, m*rad	IBS transverse time, s	IBS longitudinal time, s	Possible use of e-cooling
2.5	7 hours	4 hours	No cooling needed
1	0.96 hour	1.4 hour	Transverse pre-cooling at the injection only
0.5	13.5 min	35 min	Pre-cooling at the injection and maintaining emittances at the store

Staged Cooling: Stage 1

- Magnetized electron cooling system similar to eRHIC ZDR
  - Transverse pre-cooling of protons and heavy ions at the injection energy
  - Maintaining emittances of heavy ions at the store energy

Parkhomchuk's empiric formula for the e-cooling time:

$$\tau_{cool} = \frac{\pi^{3/2}\beta^3 (\gamma\varepsilon_n)^{5/2}\sigma_s A}{\sqrt{2}\Lambda_c r_p r_e c\eta\sqrt{\beta_{ic}} N_e Z^2} = C_{cool}\frac{A}{Z^2}\frac{(\gamma\varepsilon_n)^{5/2}\sigma_s}{N_e}$$

$$\eta = \frac{L_{cool}}{L_{circum}} \approx 0.02$$

Required electron current (28 MHz RF system, 400kV):

- 150 mA for ~30min cooling time
- 300 mA for ~15min cooling time

Staged Cooling: Stage 1 parameters

e-cooler parameters for Stage 1:

- Electron beam energy:
  - 14 MeV for pre-cooling at the injection
  - up to 55 MeV to maintain Au emittance at the store
- 150-300 mA electron current
- Energy recovery linac
- 3 T solenoids, 80 m total length

Only transverse cooling is needed! Down to 1E-6 m normalized emittance.
To prevent the longitudinal cooling, a longitudinal noise has to be introduced.

- Magnetized electron cooling itself is well proven (at low energies) and established technology.
- Technological challenges: high-current ERL, solenoid field tolerances, bunched beam cooling
- Low energy bunched beam electron cooling (non-magnetized) will be used in RHIC: 2018-2020

Staged Cooling: Stage 2

- Pre-cooling at the injection + magnetized electron cooling at the store to maintain emittances:
  - 0.5e-6 m transverse emittance
  - 1.6 eV*s longitudinal bunch area
  - proton bunch intensity: 2E11/bunch (space charge limited at the injection)

Critical number of cooler electrons to balance the cooling and IBS rates:

$$N_e = \frac{C_{cool}\left(\gamma\varepsilon_n\right)^{5/2}\sigma_s\left(A/Z^2\right)}{\tau_{IBS}}$$

e-cooler parameters for Stage 2:

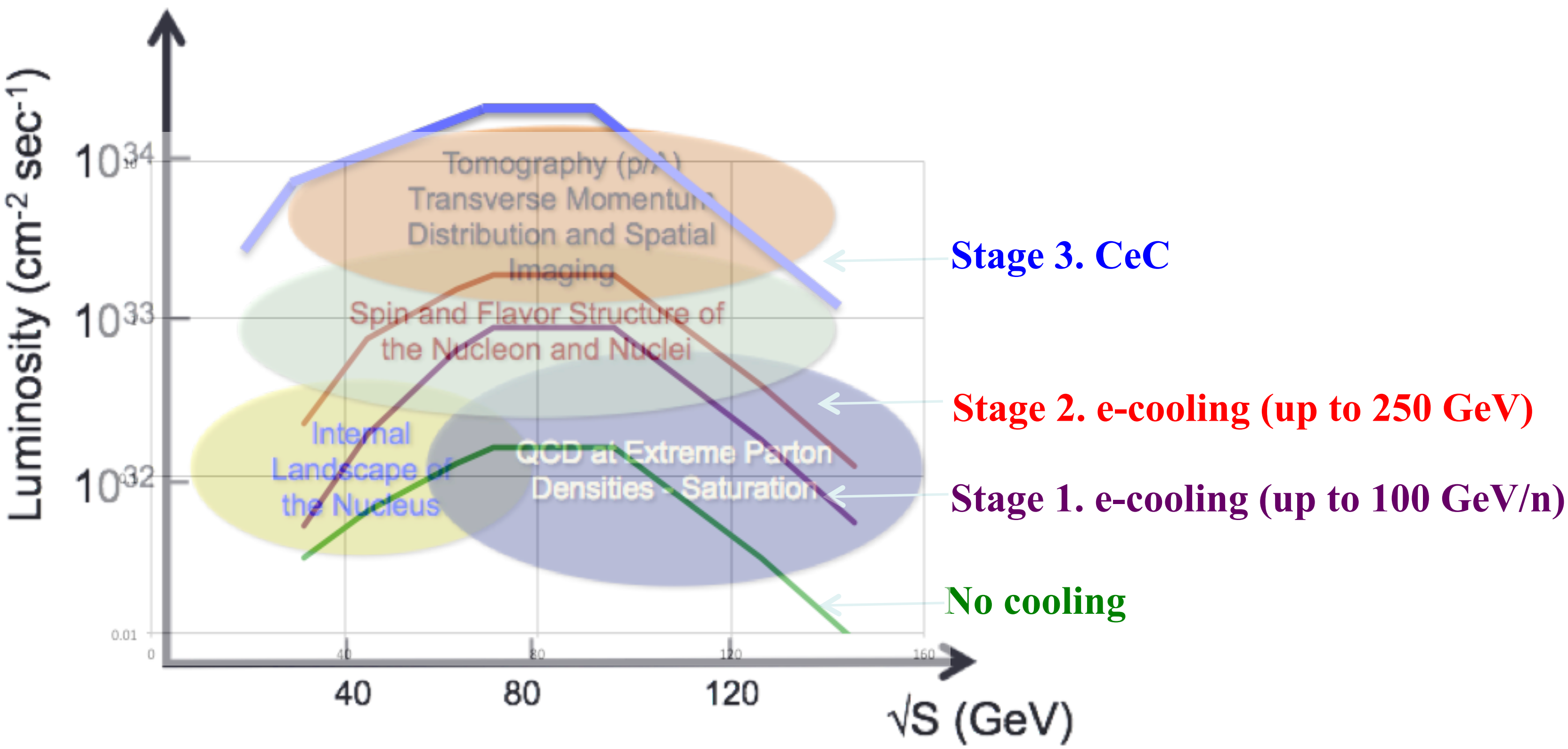
- up to 136 MeV electron beam from ERL
- up to 400 mA electron current
- 3 T solenoids, 80 m total length

Beam parameters and luminosities for highest luminosity e-p collision mode

	e	p, stage 1	p, stage 2	p, stage 3
Energy, GeV	9.2	250	250	250
CM Energy, GeV		96	96	96
Bunch intensity (nucleons), 10^{11}	0.33	3	2	3
Bunch charge, nC	5.3	48	32	48
Beam current, mA	50	415	277	415
Hadron rms normalized emittance, 1e-6 m		1	0.5	0.27
Electron rms normalized emittance, 1e-6 m		68	34	18
β, cm (both e and p)*		25	12.5	6.8
Hadron angular spread at IP, murad		123	123	123
Hadron beam-beam parameter		0.004	0.008	0.015
Space charge parameter		0.004	0.005	0.058
Electron beam disruption		10	27	34
rms bunch length, cm	0.4	20	20	5
Hourglass parameter		0.89	0.72	0.84
Peak luminosity, x 10^{33}, $cm^{-2}s^{-1}$		0.87	1.9	11

Luminosity staging based on cooling staging

e-p peak luminosity for different cooling options vs CME



Electron current risks

- Polarized electron source: 50 mA

State-of-the-art JLab polarized source:

- Up to 200 μA is produced for CEBAF operation;
- 4 mA demonstrated in dedicated experiments (10 mA with very short cathode lifetime)

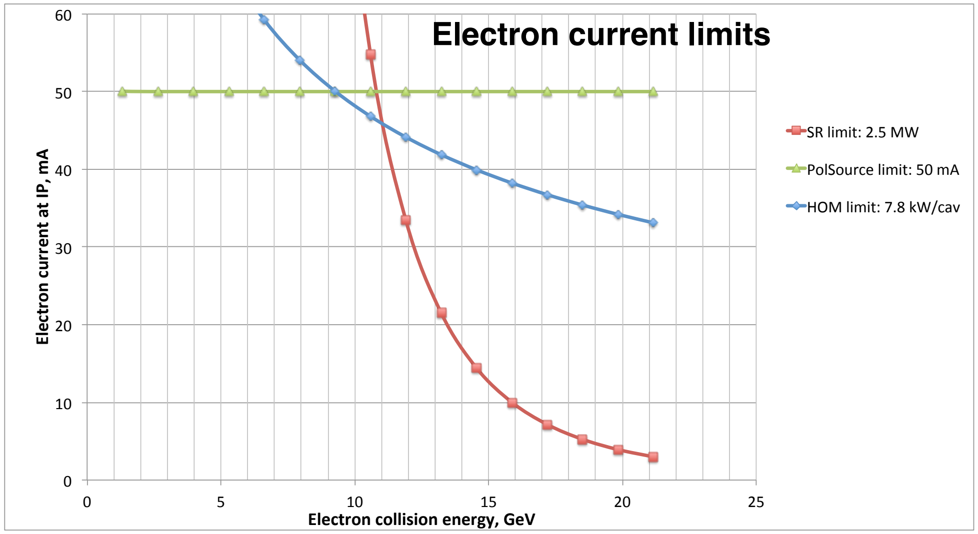
Possible backup solution: merging bunches from multiple standard polarized guns

- High current issues in ERL: Multipass BBU; HOM power damping: ~8kW/cav (in 0.5-30 GHz range); Beam loss control/ machine protection

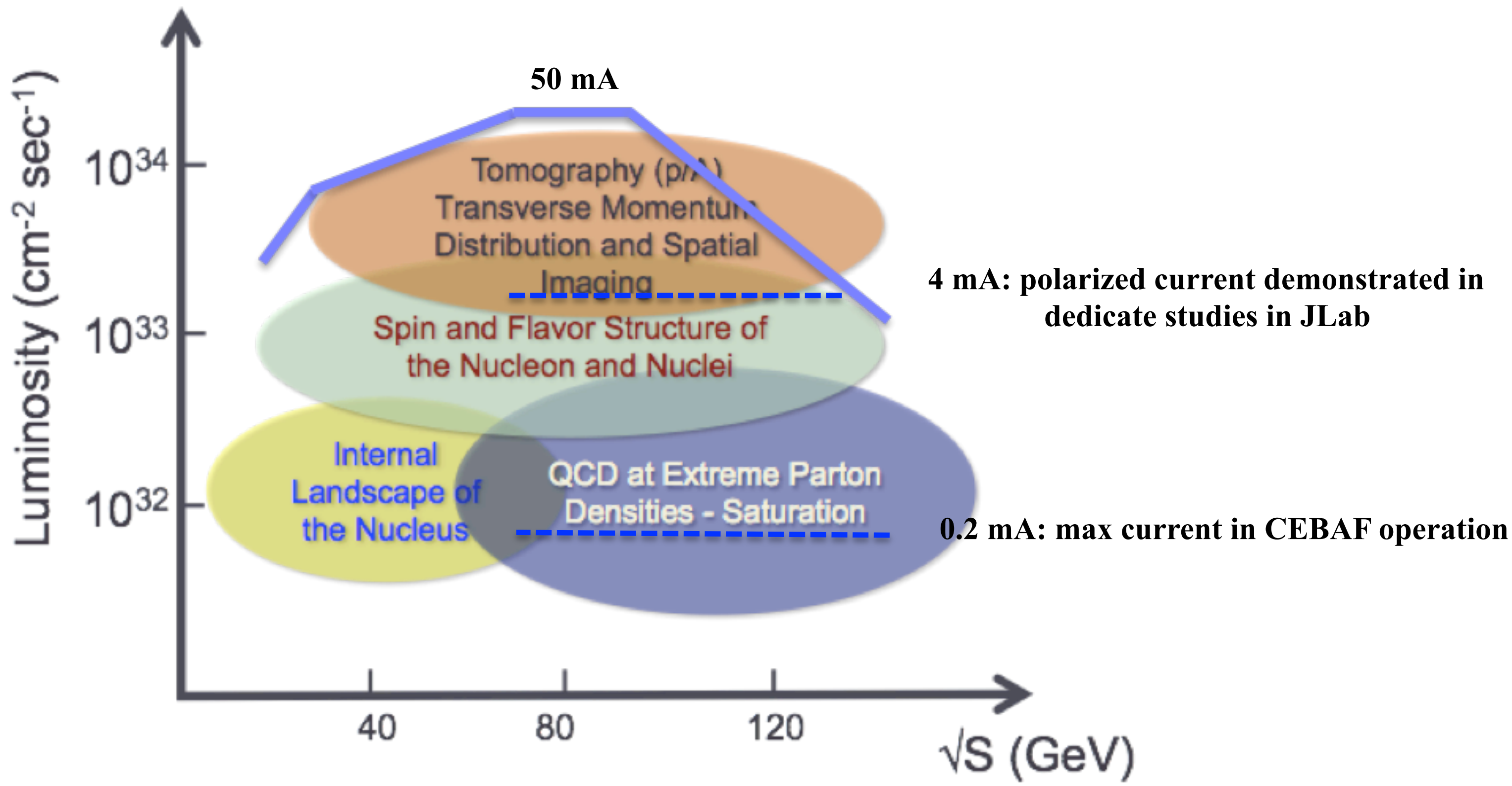
State-of the-art HOM power dampers:

- KEK-cERL: 180 W
- LHC antenna absorbers: up to 1 kW
- Jlab waveguide-type (design, prototype): few kW
- KEK-B warm pipe absorbers: >10 kW

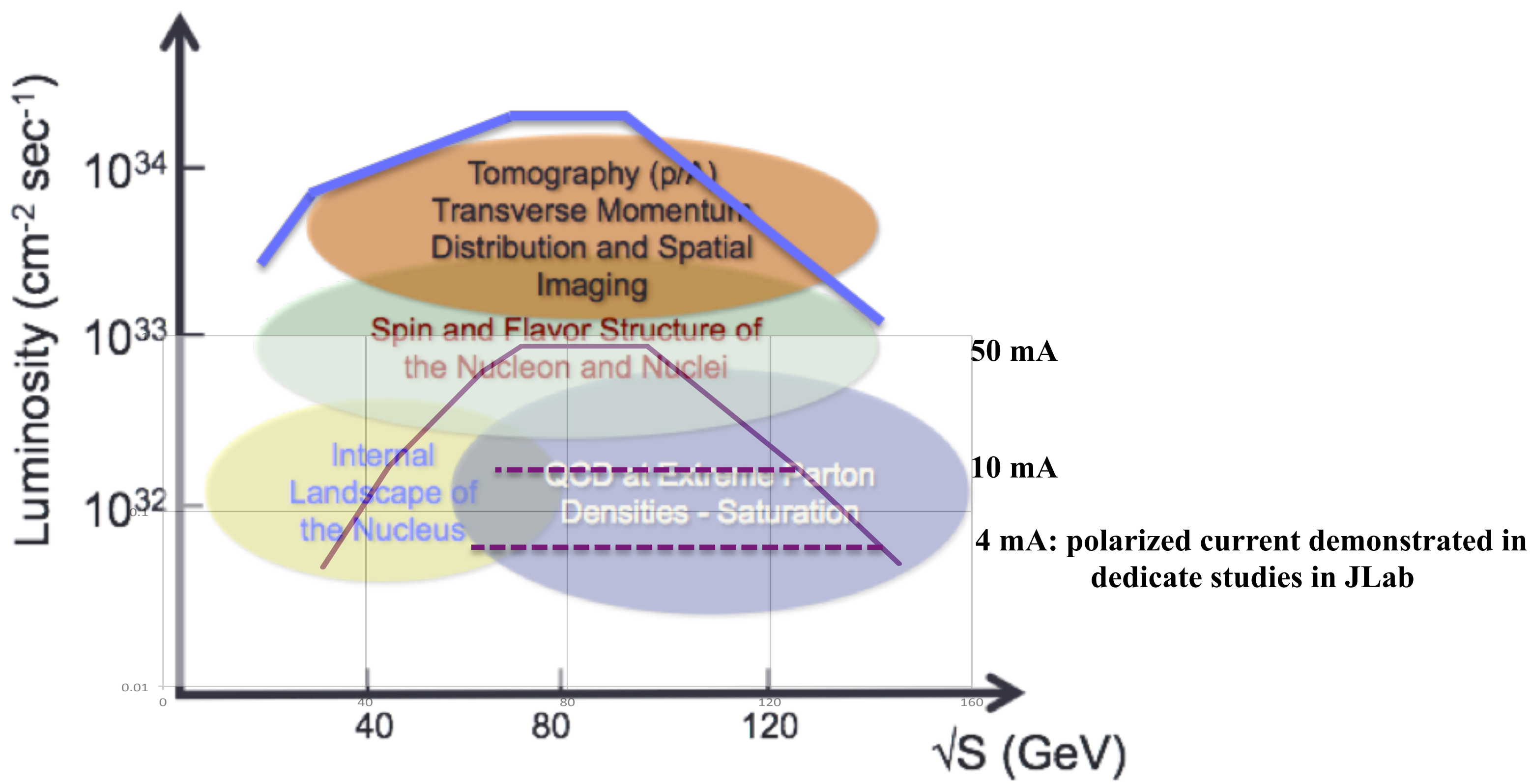
(see W.Xu's presentation for addressing HOM damping risk)



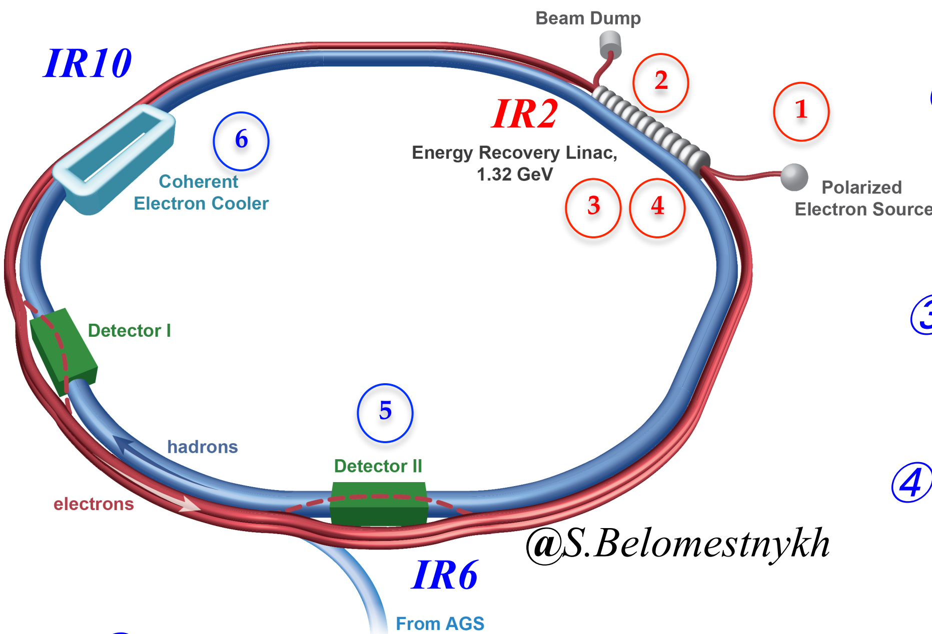
Luminosity at different electron currents for CeC



Luminosity at different electron currents for Stage 1 e-cooling



Large number of SRF cavity types



① *12 MeV injector*: 84.5 MHz and 253 MHz QWR bunchers; 422 MHz booster cavity (3-cell, 11.3 MV/m).

② *Main 1.322 GeV SRF linac*, operating at 422 MHz. The final ERL energy is 15.9 GeV with 12 passes and 21.2 GeV with 16 passes: 42 five-cell cavities operating at 18.5 MV/m.

~~③ *844 MHz (second harmonic) SRF linac* for energy loss compensation: 6 two-cell cavities, delivering 400 kW per cavity.~~

~~④ *5th harmonic (2.1 GHz) SRF linac* for energy spread compensation: 8 five-cell cavities operating at 18.7 MV/m.~~

~~⑤ *SRF crab cavities* for hadrons and electrons around detectors. The former system will include 2nd and 3rd harmonics cavities for linearization. RF frequencies: 225 MHz, 450 MHz, 676 MHz (4, 2, 1 cavities at each side of the detector for ions plus one 676 MHz cavity for electrons.)~~

⑥ *SRF ERL for Coherent Electron Cooling* (CEC) of the hadron beam. A 84.5 MHz QWR *SRF gun as an injector*, 26 QWR SRF cavities operating at 84.5 MHz and 9 QWRs operating at 253 MHz.

Cost/effort risk: total of 10 SRF cavity types to be designed, developed, prototyped.

Eliminating energy spread compensation cavities

- 5th harmonic cavities (2.1 GHz). To compensate the energy spread produced by the RF curvature of main linac waveform.

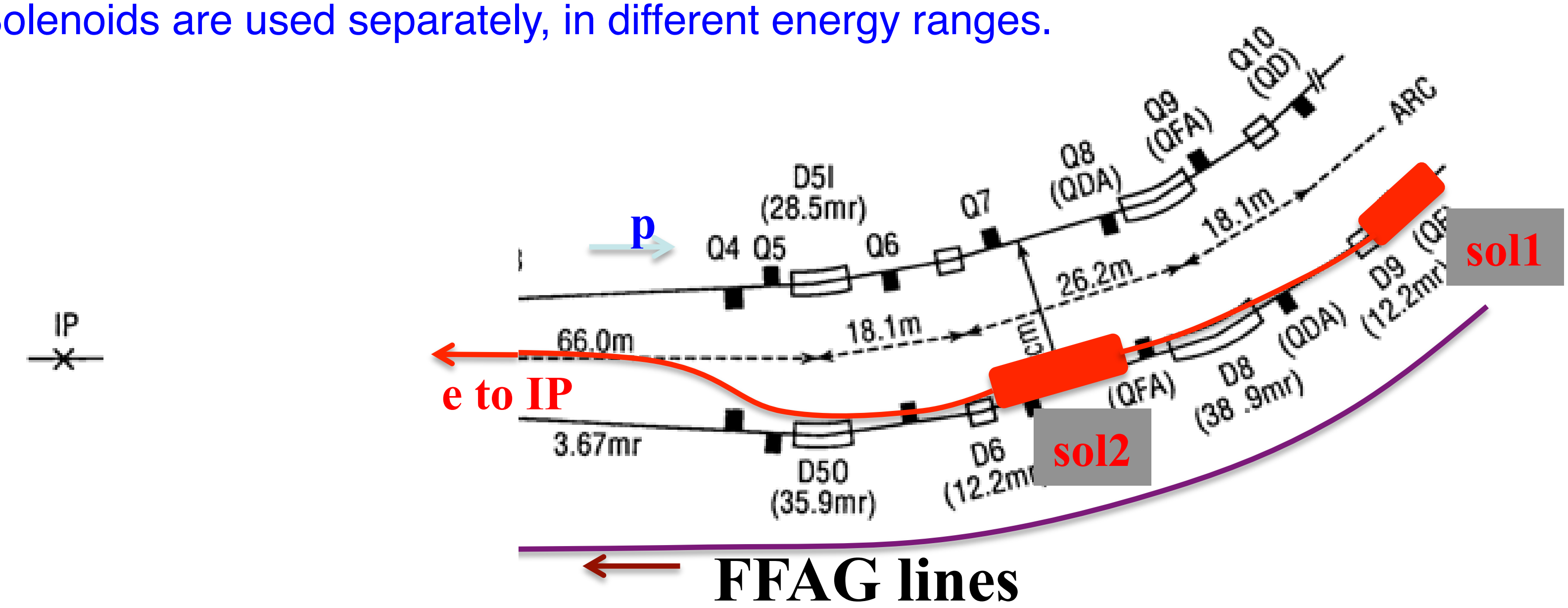
- Main purpose: preventing spin de-coherence caused by large energy spread during electron acceleration.

- The need in these cavities may be eliminated by using the spin rotator at some distance from the interaction region.
  - Spin Rotator schemes have been developed based on solenoidal magnets. Max required field integral: 110 T*m.

- Longitudinal transport simulations: on slide 23

Solenoidal spin rotators for eRHIC

Each solenoid rotates spin by 90 degrees.
Solenoids are used separately, in different energy ranges.



	Operation range, GeV	Field integral range, T*m	Orbit angle from IR	Area of RHIC tunnel	Solenoid length for 7T field
Sol1	5-10	26-53	92 mrad	D9-D10	7.6 m
Sol2	10-20	52-105	46 mrad	D6-Q8	15 m

IR without crab-crossing

- Benefits of eliminating the crab-crossing scheme:
  - Reduces number of cavity types (by 3).
  - Eliminates beam dynamics risks associated with hadron crabbing.
  - Allows for longer bunches; relaxes electron cooling requirements.

Two schemes of interaction region without crab-crossing is under consideration:

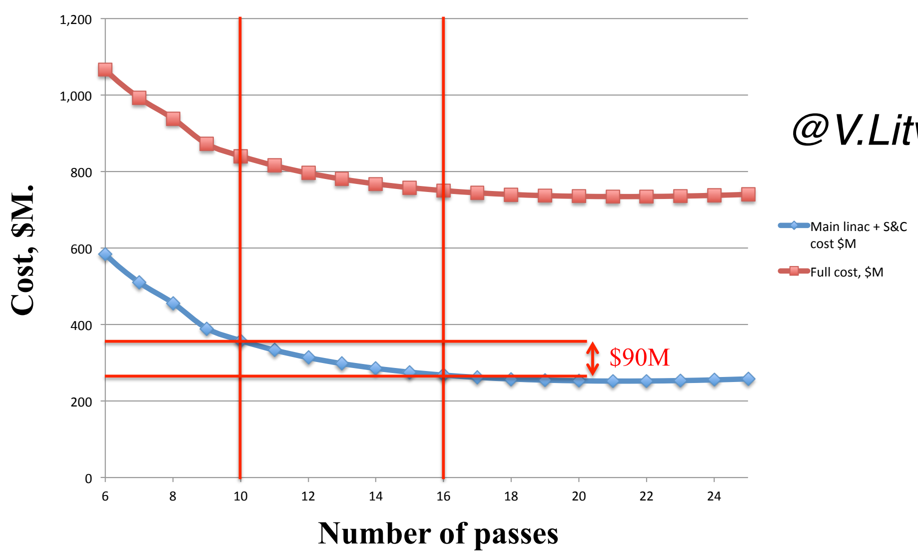
- Detector-integrated dipole (DID).
- Separation with a dipole just aside the detector (with lower luminosity).

Work on evaluating feasibility of these schemes is underway:

- Both schemes contain considerable challenges with the relation to accommodating synchrotron radiation and fully satisfying detector acceptance requirements.
- DID scheme also presents a challenge for detector systems (may require novel technologies).

Increasing linac length

- Balancing design risk reduction vs cost increase
  - Benefits of longer linac and smaller number of re-circulations:
  - Less total current in the linac
  - Less HOM power per cavity
  - Simpler spreader/merger design
  - Less energy ratio in FFAG beamlines
  - Less orbits in FFAG beamlines: simpler beam orbit control
  - Less synchrotron radiation (or larger luminosity at the same SR power)
  - Less accumulated effect of wakefields in recirculation passes (a possibility of smaller pipe aperture)
- But, increased cost:



@V.Litvinenko

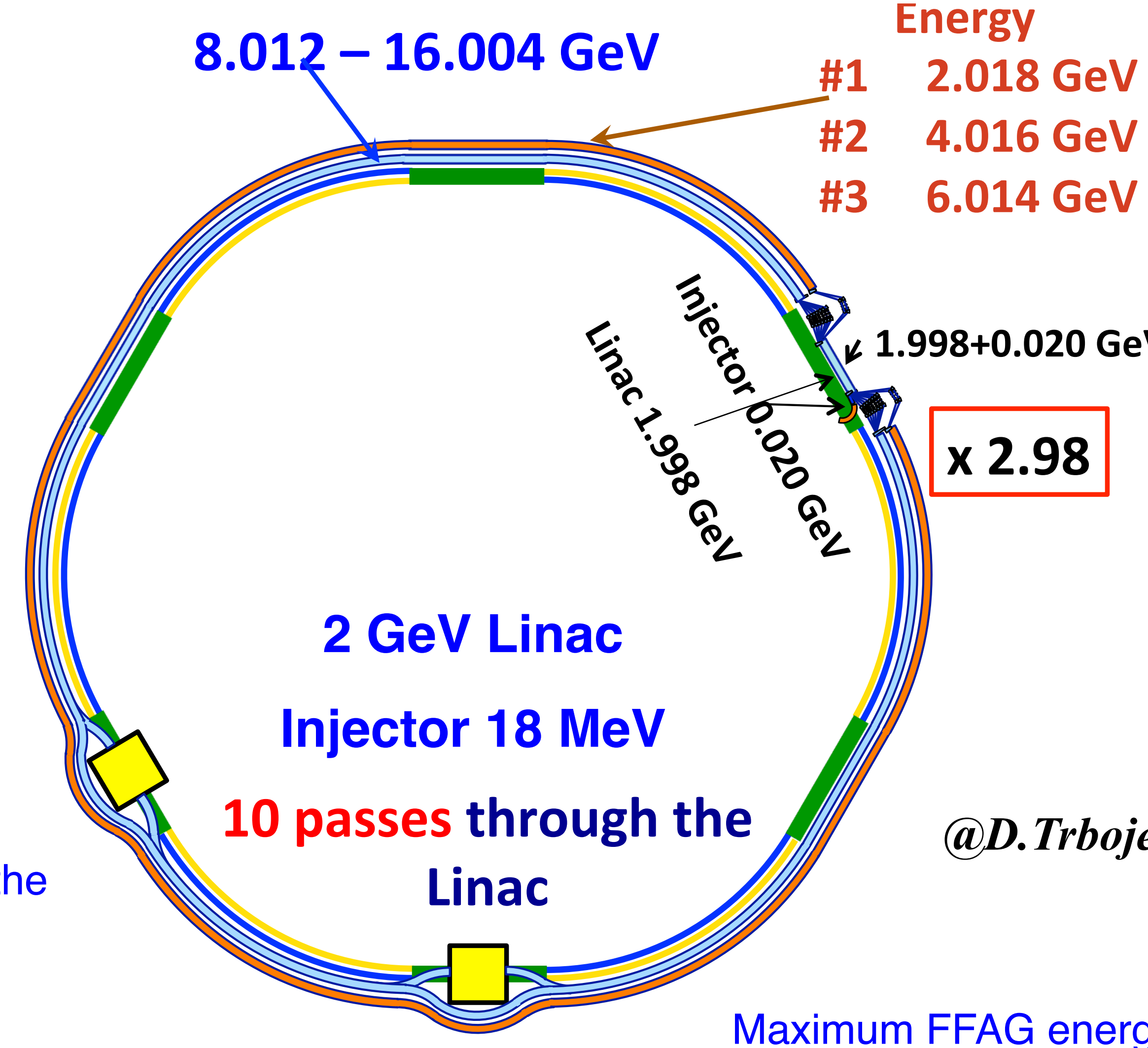
FFAG layout with 2 GeV linac

Energy

- #1 8.012 GeV
- #2 10.010 GeV
- #3 12.008 GeV
- #4 14.006 GeV
- #5 16.004 GeV
- #6 18.002 GeV
- #7 20.000 GeV

Energy

- #1 2.018 GeV
- #2 4.016 GeV
- #3 6.014 GeV



x 2.98

x 2.46

@D.Trbojevic

SR power: 1.33 MW (instead of 2.4 MW in the baseline design)

20 re-circulations (instead of 32 in the baseline design)

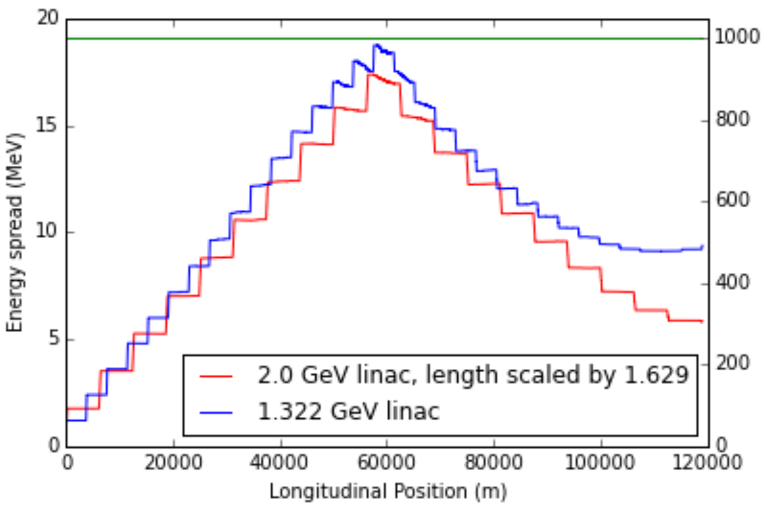
Maximum FFAG energy ratio is ~3 (instead of 4 in the baseline design)

Longitudinal transport simulations for 20 GeV operation

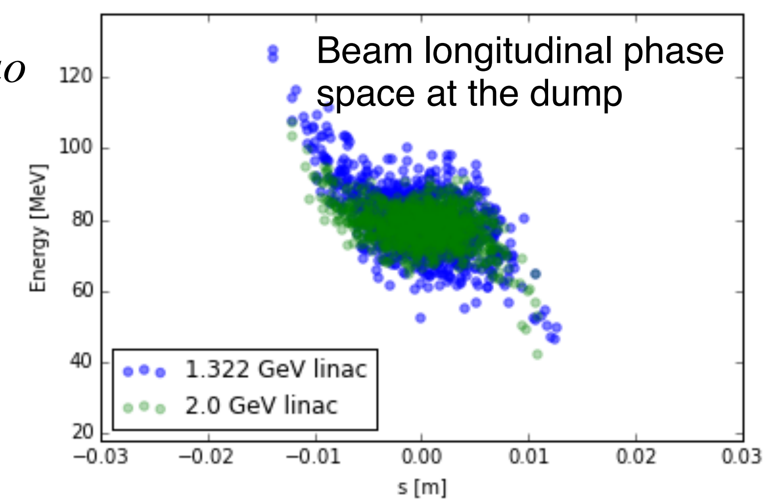
Beam transport without energy spread compensation cavities.

The goals are:
- ➢ Keep relative rms energy spread at acceleration less than $3 \cdot 10^{-3}$ in FFAGs (for transverse emittance preservation)
- ➢ Have the full energy spread at the dump less (at least by factor 2) than the dump energy.

Energy spread during the acceleration/deceleration transport was minimized by using R_{56} and pathlength knobs of individual recirculations:
- Relative rms energy spreads for both cases are less than $2 \cdot 10^{-3}$ at acceleration.
- For 2 GeV linac case the energy spread at the dump by ~40% less.



@Y.Hao



The results are shown for 2 GeV linac case as well as for 1.32 GeV linac (present baseline)

Summary: Low risk ERL-ring eRHIC

As result of this study the **Low risk ERL-ring staged eRHIC design** is proposed as follows:

- 2 GeV main Energy Recovery Linac; 2 FFAG beamlines used for re-circulations of 10 beam energies

  Many simplified design issues

- IR design without crab-crossing

- No dedicated energy loss and energy spread compensation cavities

  Number of required SRF cavity types reduced to 5.

- Stage 1 electron cooling system: pre-cooling of hadrons at the injection, maintaining emittances of heavy ions at the store

- Maximum polarized electron current at the level of 50 mA.
  (Unpolarized current for e-A experiments can be higher than 50 mA at the energies below 10 GeV)

Summary: Staging scenario

The luminosity staging scenario can be realized along the staged cooling line:

- Stage 2: upgrading e-cooling to maintain the proton emittances in stores
- Stage 3: upgrading to Coherent electron Cooling